4.0 DEVELOPMENT OF GROUNDWATER MODEL

Numerical groundwater flow modeling was used to predict the regional impacts of CBM development in the PRB. Modeling was necessary because of the large extent of development, geographic variability throughout the basin, and cumulative stresses imposed by mining and CBM development on the Fort Union and Wasatch aquifer units. Impacts from development of CBM have been evaluated in earlier environmental assessments for the Marquiss, Lighthouse, North Gillette, South Gillette, and Wyodak development areas (USDI BLM 1992, 1995, 1996, 1997, and 1999). The information from earlier studies was reviewed and has been incorporated wherever practical into modeling for the PRB Oil and Gas EIS.

Numerical groundwater models can be particularly useful tools for refining the conceptual model of the groundwater flow systems within a regional basin. A calibrated numerical groundwater model ensures that groundwater flow systems are reasonably consistent with all hydrogeologic data, including all data from groundwater monitoring and aquifer testing available over most parts of the basin. Transient calibration of the model to measured mine water inflows, CBM well production, river baseflow, and measured drawdown in overlying and underlying zones, as well as the stressed zone, is a particularly effective method for refining the conceptual model of the groundwater flow systems. The horizontal and vertical hydraulic conductivities for individual model layers, developed using transient model calibration and vertical gradient data, provide more definition concerning the interconnectivity of the hydrogeologic units.

Any numerical groundwater model of a regional basin is a simplification of a complex hydrogeologic system. There is never a unique set of calibration parameters for any model. Nevertheless, the calibrated model should be reasonably consistent with hydrogeologic observations, and particularly with information that is developed on a regional scale, even if the data available to calibrate the model are relatively sparse. There are several parameters that are used to calibrate the model in both steady state and transient state. For example, in steady state, model results are compared with premining groundwater elevation in wells. Another consideration in model calibration is that modeled groundwater discharge rates must be consistent with observations of contributions from river baseflow (Section 2.3.3).

The regional model is an adequate tool for the analysis of the effects of CBM development, but the results should be used with caution when considering a sub-regional or local area. The regional model is constructed using averaged and smoothed values so that localized conditions typically are not highly refined.

Two sub-area models, developed at a much smaller scale, complement the regional model and were used to demonstrate specific aspects of CBM development in the PRB. The Caballo Creek sub-area, model described in Chapter 8, was used to match data on transient conditions in an area having a relatively long history of CBM development. This sub-area model allowed an evaluation of hydrologic parameters for confining zones that have a major influence on projections of shallow aquifer drawdown and coal recovery after CBM pumping ceases. The LX-Bar sub-area, model described in Chapter 9, was developed specifically to examine the potential influences of infiltration impoundments on groundwater levels in shallow Wasatch sands and adjacent creek flows. The sub-area model targets an area where surface discharge probably would be limited by water quality considerations.

4.1 Conceptual Model

The regional groundwater flow model for the PRB was based on the conceptual model that has its foundation in the geology and hydrogeology described in Chapter 2. The coal-bearing units of the upper portion of the Fort Union Formation are considered to have sufficient lateral continuity, and they act as a regional aquifer system. Individual coal seams split and merge; however, there is sufficient hydraulic communication on a regional scale to allow movement of groundwater from areas of recharge predominantly at the higher topographic elevations along the eastern, western, and southern margins of the basin, toward the lower topographic elevation areas along the northern margin of the basin. The structure of the Fort Union Formation is reasonably well documented and can be used as a framework for the layers in the regional model.

The Wasatch Formation is the surficial unit over most of the PRB. Most of the recharge to the basin occurs through this formation. Recharge is primarily through infiltration of runoff in the extensive network of ephemeral drainages that characterize the surface topography of the PRB. Most of the recharge occurs during the spring snowmelt. At other times of the year, the ephemeral streams are dry, except when high-intensity thunderstorms cause short-term runoff. This recharge occurs in the discrete channels of the surface drainage system, but the extensive drainage network results in an overall areal recharge when considered in a regional perspective.

Groundwater flow within the Wasatch Formation is dominated by local rather than regional flow systems. The general lack of laterally extensive transmissive units and the dissection of the shallow portions of the formation by surface drainages result in shorter, more localized flow paths from recharge to discharge areas. Much of the recharge that enters the Wasatch aquifer probably remains in a relatively shallow groundwater flow system and eventually discharges in topographically lower areas in the form of transpiration, springs or seeps. The alluvium within larger drainage channels conducts some of this shallow groundwater flow.

Over most of the PRB, the potentiometric pressure within the shallow Wasatch sandstones is higher than in the deeper Wasatch sandstones and the underlying Fort Union Formation coals. This downward hydraulic gradient induces a component of vertical groundwater flow, so that some portion of the Wasatch recharge may eventually leak into deeper regional flow systems. Low-permeability claystone and siltstone units retard the downward movement of groundwater and may locally divert flow laterally, but on a regional scale, this slow component of downward flow provides most of the recharge to the Fort Union coal zone aquifer. Some recharge to the Fort Union coals occurs in coal subcrop areas through clinker zones. Although the clinker has a high capacity for infiltration, the low permeability of the contact zone between the clinker and the underlying, unburned coal or shale usually limits the rate of recharge to the coal and may cause ponding clinker. Springs are likely to occur at the contact between the clinker and unburnt rocks.

The regional groundwater system discharges to the lower topographic valleys in the PRB, primarily to the lower reaches of the Powder, Little Powder, and Tongue Rivers in the northern portion of the PRB. The groundwater discharge is relatively small and diffuse and is not readily discernable as stream baseflow. Flowing artesian wells along the Powder River Valley form a small component of this bedrock discharge. Some discharge also occurs in the Cheyenne and Belle Fourche River drainages, but tends to be from shallow local groundwater flow systems rather than deeper regional flow systems.

4.2 Model Code

The hydrogeologic model used in this study to assess both vertical and lateral flows under various mine dewatering and CBM development scenarios is a transient (time variable), three-dimensional (multi-layered) flow model. The groundwater flow code used was MODFLOW 96 developed by the U.S. Geological Survey (USGS). This model is widely accepted by regulatory agencies and is packaged in a pre- and post processing software package, Visual MODFLOW (VMODFLOW) by Waterloo Hydrogeologic. MODFLOW is a widely accepted model code, but has limitations, which are discussed in Section 4.7. The VMODFLOW program (v.3.0.0) was used to complete pre-processing, modeling, and post-processing. The package also allows for zone water budgets. Modeled potentiometric surfaces for groundwater were exported from VMODFLOW and contoured using the software program SURFER v.7 (Golden Software) and were displayed using AutoCAD Map 2000.

4.3 Model Area

The Project Area extends from T34N R69W in the southeast to T58N R89W in the northwestern part of the PRB within Wyoming. The Project Area covers slightly less than 12,500 square miles (almost 8 million acres). The model itself encompasses the entire PRB (including the portion of the PRB within Montana) and extends a few miles beyond the Fort Union outcrop. The boundary of the model extends beyond the outcrop of the Tullock member in most of the western, southern, and eastern portions of the model area and beyond the outcrop of the upper portion of the Fort Union Formation in the north. A portion of the southwestern boundary of the model is set within the outcrop of the Tullock member. The model area is shown in Figure 4-1. The boundary of the model extends beyond the Project Area to establish boundary conditions using natural flow boundaries, such as the northern outcrop of the Fort Union Formation in Montana.

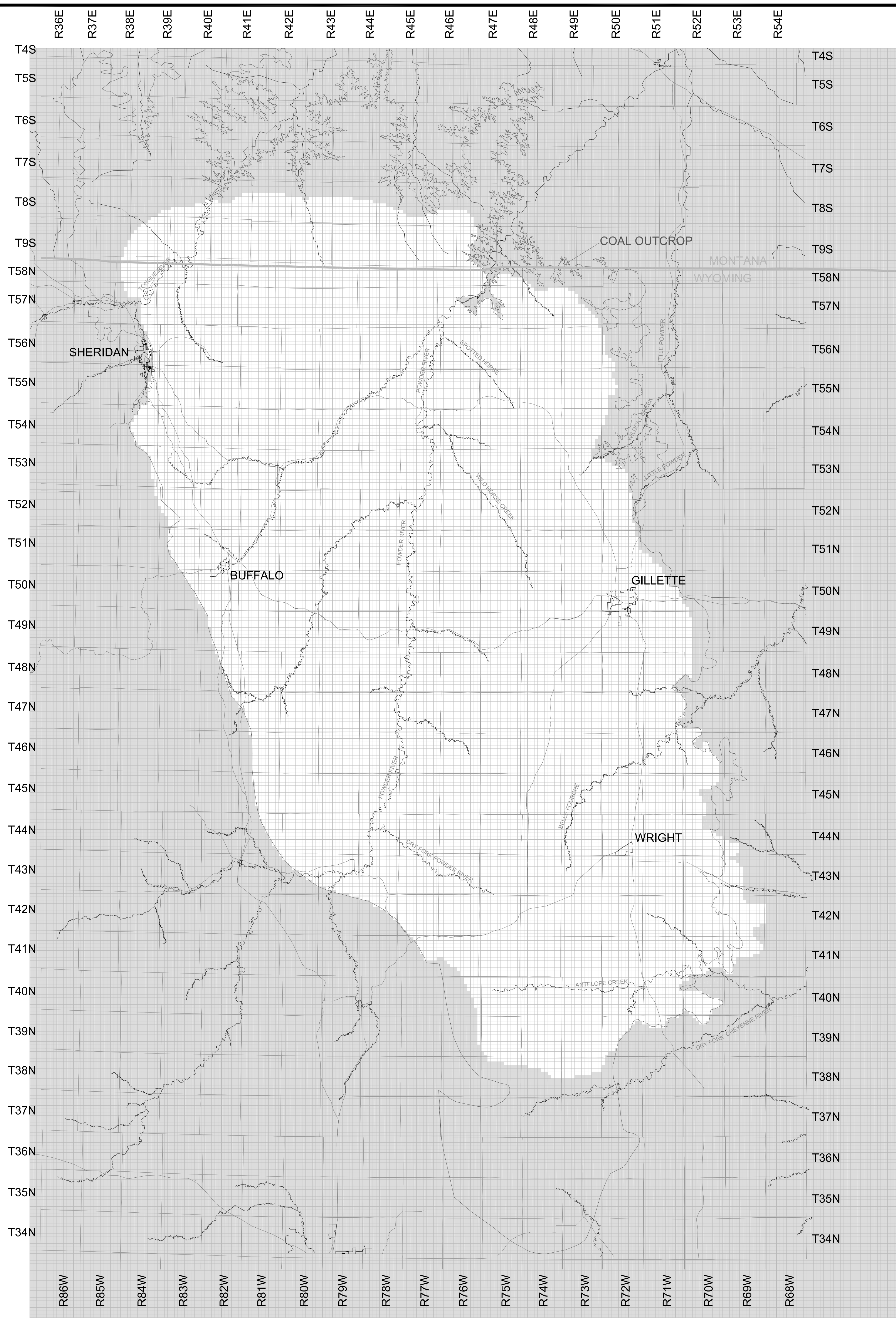
Typically, a model is oriented parallel to the axes of maximum and minimum transmissivity in the aquifers of interest so that anisotropy can be included. However, available data for the PRB indicate that, although local anisotropy exists, the directions vary regionally, and no single direction is dominant. Accordingly, the model was oriented north-south and east-west for ease of use.

4.4 Grid Setup

The model setup and assumptions are summarized in Table 4-1. The model grid (Figure 4-1) consists of 377 cells in the north-south direction (rows) and 259 cells in the east-west direction (columns), for a total of 97,643 cells per layer. The grid spacing is uniform throughout the model and is one-half mile (about 800 meters) in both the north-south and east-west directions. The uniform grid spacing allows for easier manipulation of the model in ArcView, Surfer, and MS Access, while maintaining the integrity of the model. The model grid was set up in the North American Datum (NAD) 27 Universal Transverse Mercator (UTM) Zone 13 meters coordinate system to allow easy transfer of model results into BLM's ArcView Geographic Information System (GIS).

4.5 Layer Setup

The model consists of 17 layers, which are summarized in Table 4-2. The top of the uppermost layer (Layer 1) is the topographic surface. This surface was constructed from 1:250,000 USGS digital elevation models (DEMs) that cover the entire model area. Using Surfer software, the x,y,z data from the DEMs were extracted into a .dat file. Every other point was extracted, except along the eastern boundary (which is outside the Project Area and active model domain), where every third point was extracted. The



MODEL GRID SPACING 1/2 MILE x 1/2 MILE

LEGEND

- Rivers
- Roads
- Towns
- No Flow Cells
- Model Grid

N

0 7.5 15 30 Miles

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FIGURE 4-1
MODEL AREA GRID
AND NO-FLOW NODES

MODEL RUN: From 1999-2200 (08-26-02)

Date: 09/04/02	Drawing File: Figure 4-1.dwg
Scale: As Noted	Drawn By: ETC

Figure 4-1 continued (11x17)

resolution of each original DEM is one point every 100 meters; therefore, one point every 200 meters (656 feet) was extracted. Extraction was necessary because the file was too large to grid otherwise (the row limit for Surfer is 5 million).

The extracted files (as .dat files) were combined, and, using Tralaine conversion software, the coordinates were converted from Lat/Long to NAD27 UTM Zone 13 meters. This extracted, converted file is called PRB_Topo_UTM.dat. Surfer was then used to grid this file at a spacing of one-half mile by one-half mile using the "Natural Neighbor" algorithm. Surfer was used to grid the data rather than the VMODFLOW interpolation because the gridding algorithms in Surfer are superior. The Surfer grid file was then imported into the VMODFLOW model as the topographic surface for the model (Figure 4-2).

Model layers 1 through 7 represent the Wasatch Formation. Layers 8 through 14 represent the upper part of the Fort Union Formation. The lowermost three layers (layers 15, 16, and 17) represent the lower members of the Fort Union Formation and the claystone aquitard that separates these members from the overlying coals in the upper portion of the Fort Union Formation.

The uppermost layer (layer 1) represents the surface geologic units that include shallow Wasatch geologic units (claystone, siltstone, and sandstone) and unconsolidated alluvial sands within creek valleys. This layer was assigned a uniform thickness of 30 feet (10 meters). The hydrologic properties within this layer, described later in Section 4.5, were varied to reflect the different characteristics of alluvial areas compared with the shallow Wasatch geologic units.

Layers 2, 4, and 6 represent shallow, intermediate, and deep zones of the Wasatch Formation, where discontinuous sandstone units occur. The discontinuous nature of the sandstone units is difficult to accurately simulate in a regional model with limited data. However, simulation was attempted by assigning hydrologic parameters to these layers that represent mixed sandstones and siltstone/claystone.

Layers 3 and 5 represent low-permeability claystone and siltstone units that separate the discontinuous sand units in the Wasatch Formation. Overlying the Fort Union coal zone is a layer (layer 7) which represents claystones within the Wasatch Formation that act as a confining unit between the coal zone and the discontinuous sandstones. This layer was set at a uniform thickness of 30 feet (10 meters) above the top of the coal zone in the upper portion of the Fort Union Formation. The vertical permeability of this layer in any location reflects its ability to act as a confining unit between the Fort Union coal zone and the overlying deep Wasatch sandstones. It is recognized that the assigned thickness and vertical hydraulic conductivity of this unit influence the rate of leakage from the discontinuous layers of the sandstone unit (primarily layer 6). However, since the leakage is proportional to the product of the thickness and the vertical hydraulic conductivity, the vertical permeability assigned to the layer in any area can be varied to compensate for variations in thickness.

The thickness of layer 1 was set at a minimum of 30 feet (10 meters) and follows the configuration of the surface topography. The base of layer 2, the shallow, discontinuous sand layer within the Wasatch Formation, was set at a uniform 100 feet (31 meters) below the topographic surface. The thicknesses of layers 3, 4, and 5 were created in Surfer by taking the total thickness between the base of layer 2 minus the top of layer 6, and dividing the result evenly among the three layers, and importing it into VMODFLOW. The top surface of layer 6, which represents the lower sands within the Wasatch Formation, was created by adding 100 feet (31 meters) to the top surface of the uppermost coal unit in the Fort Union Formation (layer 8). The top surface of layer 7, which represents the lower confining unit within the Wasatch Formation, was created by adding 50 feet (15.5 meters) to the surface of the uppermost coal unit (layer 8) in the Fort Union Formation. This procedure results in a uniform thickness of 50 feet (15.5 meters) for both layers 6 and 7.

Table 4-1
Summary of Regional Model Setup and Assumptions

Project	Powder River Basin (PRB) Environmental Impact Statement (EIS) - Powder River Basin Groundwater Impacts
Area	Powder River Basin in northeast Wyoming
Code	MODFLOW-96. Pre- and post-processor: VMODFLOW v.3.0.0
Time modeled	Steady State: 1975 (Pre-mining); Transient State: 1975 to 2200
Dimensions	X = 208.6 Km, Y = 303.3 Km (63,255 Km^2, 24,423 sq. miles)
X coords	317,470 – 526,025 m
Y coords	4,732,100 – 5,035,400 m
Coordinates	NAD27 UTM Zone 13, meters
Rows, columns	No. of rows: 377 No. of columns: 259 (97,643 cells/layer)
Grid spacing	804.6 m x 804.6 m (½ mile x ½ mile) for the entire model
Layers/type	No. of layers: 17. Layer 1: Unconfined: Layers 2-17 Variable T, S
Surfaces	**Coal surfaces and isopachs:** Established from data provided by Goolsby, Finley and Associates (2001) **Steady-state potentiometric surface:** Modified after Daddow 1986, U.S. Geological Survey (USGS) Ground-Water Resources of Sheridan County 1966, Bureau of Land Management (BLM) Well Data, Wyoming State Engineers Office Well Data **Surface topography:** USGS digital elevation models (DEMs)
Geology	**Coal Units:** Goolsby, Finley and Associates (2001) **Surface Geology:** USGS: "National Coal Resource Assessment, 1999 Resource Assessment of Selected Tertiary Coal Beds and Zones in the Northern Rocky Mountains and Great Plains Region" (USGS 1999a)
No-flow Boundaries	The no-flow boundary of each layer is different and is determined by the formation the layer represents.
Infiltration	Basin-wide infiltration: 0.03 inches per year Clinker infiltration: 0.1 to 0.6 inches per year Infiltration for each sub-watershed fluctuates depending on how much water is produced by the CBM wells and the prevailing water management practices.
Rivers (constant head)	**Perennial Rivers:** Set as constant head nodes trending linearly downstream between two topographic elevations. The perennial rivers are: Powder River, Belle Fourche River, Clear Creek, Crazy Woman, and Tongue River. **Intermittent Rivers**: Major ephemeral rivers set as drain nodes with the drain node elevations trending linearly downstream between points of the topographic surface. **Flow to the Yellowstone River**: Drain nodes were put in the lowest layer in the north to allow flow "out of the model," which mimics flow toward the Yellowstone River.
Southwest Inflow (constant head)	Inflow from the southwest into the model area was simulated using constant head cells with an elevation equal to the top of the coal zone.
Coal Mines and CBM Wells	**Mine plans and locations**: Wyoming Department of Environmental Quality (WDEQ) and Office of Surface Mining (OSM) annual reports from mining companies; Gillette Area Groundwater Monitoring Organization (GAGMO) 15-year report, GAGMO 2000 Data. **CBM Wells:** Put in as drain nodes. Existing coal bed methane (CBM) wells taken from the Wyoming Oil and Gas Conservation Commission (WOGCC) database dated 7/20/01. Projected CBM wells developed by BLM, WOGCC, Greystone, Applied Hydrology Associates (AHA) with input from CBM industry representatives.
Solver	Steady-state: WHS (Waterloo hydrologic solver); Transient-state: WHS.
Rewetting	Set to rewet from the sides and below. Rewetting interval is 15 threshold is 5 m, increment is 0.1 m.

Table 4-2
Regional Model Layers

Model Layer	Geologic Formation/Member	Geologic Unit	Predominant Lithologies
1	Wasatch Formation	Upper Wasatch Formation and Alluvium	Sandstone, siltstone, claystone
2		Shallow Wasatch Sands	Sandstone, siltstone
3		Confining unit within Wasatch Formation	Siltstone, claystone
4		Intermediate Wasatch Sands	Sandstone, siltstone
5		Confining unit within Wasatch Formation	Siltstone, claystone
6		Deep Wasatch Sands	Sandstone, siltstone
7		Confining unit at base of Wasatch Formation	Siltstone, claystone
8	Fort Union Formation	Upper Fort Union Coal (Unit 1)	Coal (minor sandstone, siltstone)
9		Confining unit between coal units	Siltstone, claystone
10		Upper Fort Union Coal (Unit 2)	Coal (minor sandstone, siltstone)
11		Confining unit between coal units	Siltstone, claystone
12		Upper Fort Union Coal (Unit 3)	Coal (minor sandstone, siltstone)
13		Confining unit between coal units	Siltstone, claystone
14		Upper Fort Union Coal (Unit 4)	Coal (minor sandstone, siltstone)
15		Confining unit at base of coal units	Siltstone, claystone
16		Lower Fort Union Formation	Sandstone, siltstone, claystone
17		Lower Fort Union sand aquifer units	Sandstone, siltstone

The top and bottom surfaces of the four coal-bearing hydrogeologic units of the upper part of the Fort Union Formation, represented by Layers 8, 10, 12, and 14, were created from unpublished data compiled and consolidated by Goolsby, Finley, and Associates (2001) for the modeling effort. As the coal-bearing units split and merge in the PRB, the hydraulic properties assigned to the layers that represent both coal-bearing units and intervening units change accordingly. The coal-bearing units transition into clinker that is more highly permeable in outcrop areas.

Goolsby, Finley, and Associates (2001) provided the data for the Fort Union coal zone (such as for the top of unit and base of unit) for the entire basin at a density of one representative data point per township and up to four different coal units per point. Surfer was used to grid the data (which was provided in an Excel spreadsheet) at a one-half mile by one-half mile spacing, and the grid file was imported into VMODFLOW. The interpretation of the data shows only one distinct coal unit in some areas of the basin, while up to four distinct coal units may be found in other areas. The distribution of coal groupings is described in Chapter 2 and is illustrated in Figure 2-2.

In reality, there are more than four coal units in some parts of the basin, but, because of the limitations of the model, the maximum number of modeled coal units was held to four. Where coal units merged in the model, the total thickness of the coal was divided among the associated model layers. For example, coal units 1, 2, and 3 in the southern part of the basin (which have been arbitrarily named and are represented in the model by layers 8, 10, and 12) merge into one coal unit. In the model, the thickness of the coal unit was divided evenly among layers 8 through 12 and all of the layers were assigned coal properties. Dividing the thickness of the coal unit among all five layers provided better vertical discretization in the model. The alternative would be one very thick coal unit and four very thin underlying units, which could have led to numerical instability.

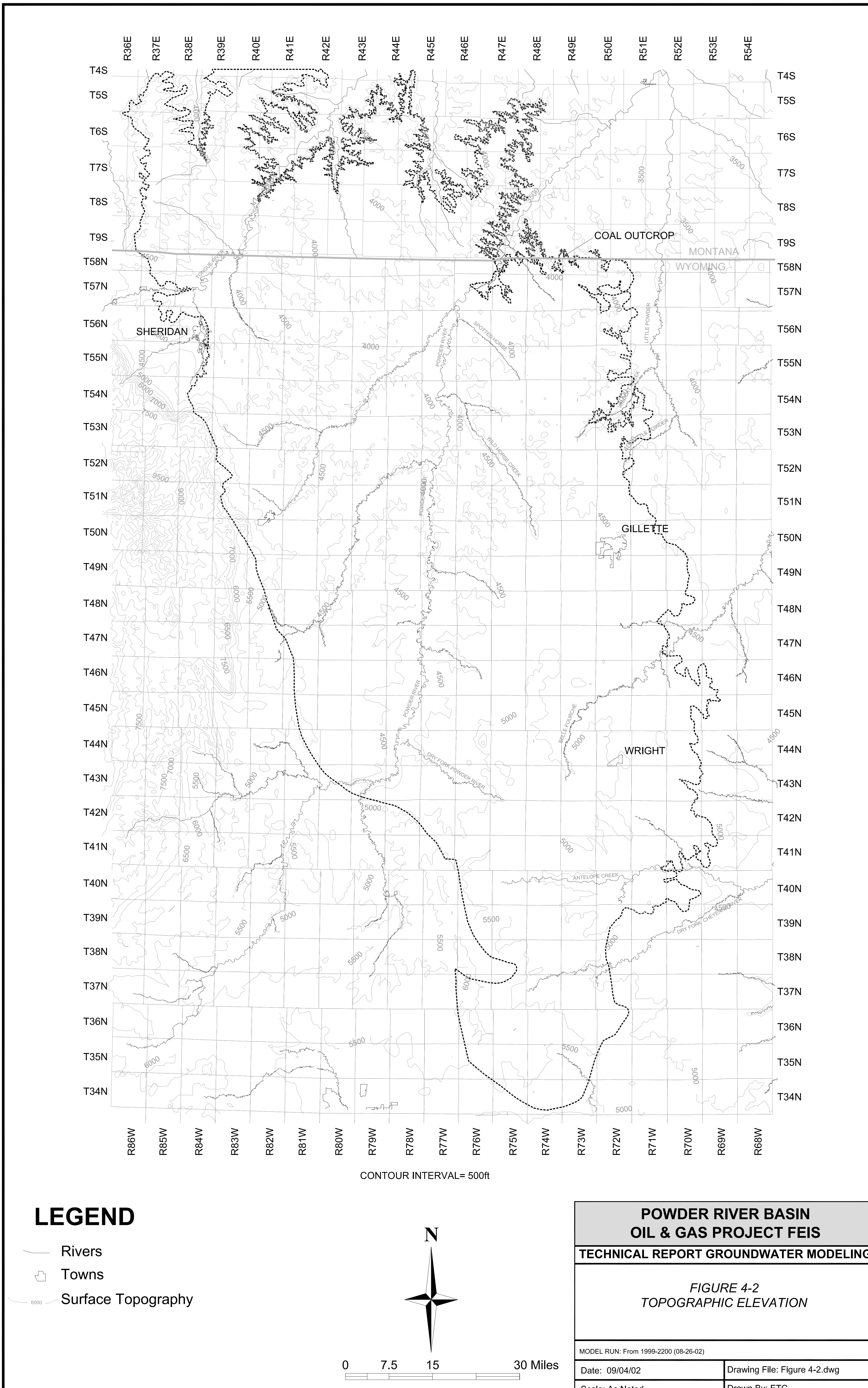

R36E R37E R38E R39E R40E R41E R42E R43E R44E R45E R46E R47E R48E R49E R50E R51E R52E R53E R54E
T4S T5S T6S T7S T8S T9S
T58N T57N T56N T55N T54N T53N T52N T51N T50N T49N T48N T47N T46N T45N T44N T43N T42N T41N T40N T39N T38N T37N T36N T35N T34N
R86W R85W R84W R83W R82W R81W R80W R79W R78W R77W R76W R75W R74W R73W R72W R71W R70W R69W R68W
COAL OUTCROP
MONTANA
WYOMING
SHERIDAN
GILLETTE
WRIGHT
POWDER RIVER
SPOTTED HORSE
WILD HORSE CREEK
LITTLE POWDER
BELLE FOURCHE
DRY FORK POWDER RIVER
ANTELOPE CREEK
DRY FORK CHEYENNE RIVER
CONTOUR INTERVAL= 500ft
LEGEND
Rivers
Towns
Surface Topography
N
0 7.5 15 30 Miles
POWDER RIVER BASIN
OIL & GAS PROJECT FEIS
TECHNICAL REPORT GROUNDWATER MODELING
FIGURE 4-2
TOPOGRAPHIC ELEVATION
MODEL RUN: From 1999-2200 (08-26-02)
Date: 09/04/02
Drawing File: Figure 4-2.dwg
Scale: As Noted
Drawn By: ETC

Figure 4-2 continued (11x17)

Beyond the coal outcrop, the model layers that represent the coal units were assigned elevations equal to the surface topography. In this way, all coal and intervening layers were extended to the surface (less the minimum thickness). Surfer was used to combine the data for the Fort Union coal units within the coal outcrop and the topographic data outside the coal outcrop.

The lowermost three layers (layers 15, 16, and 17) represent the lower members of the Fort Union Formation and the claystone aquitard that separates these members from the overlying coals in the upper portion of the Fort Union Formation. The claystone aquitard (Layer 15) was set at a uniform thickness of 50 feet (15.5 meters) below the base of the Unit 4 coal group. The vertical permeability of this layer in any location reflects its ability to act as a confining unit between the upper Fort Union coal zone and the underlying sequence of the Fort Union Formation.

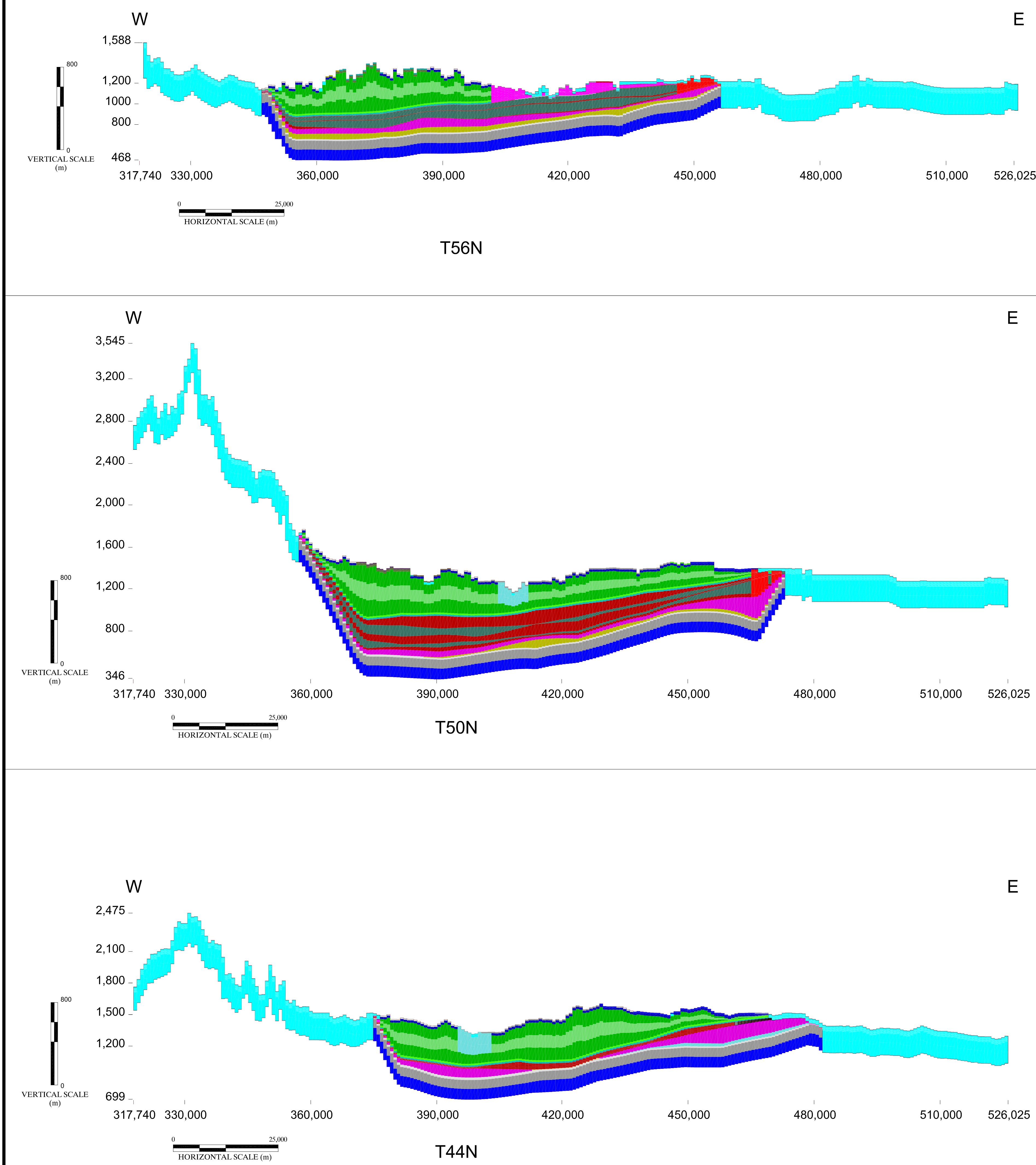
The sandstones in the lower portion of the Fort Union Formation form an aquifer that is tapped by many of the municipal supply wells in Campbell County. Layer 16 represents a transition zone, and layer 17 simulates the zone of relatively permeable sandstone units in the lower Tongue River/Lebo members of the Fort Union Formation. Layer 16 was set at a uniform thickness of 280 feet (85 meters), and layer 17 was set at a uniform thickness of 325 feet (100 meters). Claystones within the lower portion of the Fort Union Formation form the impermeable base of the model.

MODFLOW is a finite difference model and, consequently, every layer is continuous throughout the model. These continuous layers become problematic in modeling basin type structures (or non-continuous units) because, in reality, the geologic unit outcrops (terminates) while the layer that represents that unit must be continuous in the model. In addition, a minimum thickness must be associated with each node. At and beyond outcrop areas, the model will create an artificial thickness for the layer beyond the outcrops, and all layers below are displaced downward by that thickness. As more layers "outcrop," the magnitude of artificial thickness increases. For this model, the minimum thickness of each layer was set at 3 meters. The model layers above the coal near the outcrop (excluding the alluvium) were linearly decreased to a thickness of 3 meters using Surfer to minimize the effects of displacement on the coal units. However, it is impossible to avoid some displacement. At worst, the lowest coal might be displaced downwards by 46 meters (Layer 1 = 10 meters, Layers 2 through 13 = 3 meters). Inserting no-flow cells in the layers where the unit represented outcrops and applying recharge to the highest active cell further mitigates the effects of displacement.

Three typical cross-sections that show the setup of the model layers and the variability in the thickness of each layer are shown in Figure 4-3. The locations of the three cross-sections are shown in Figure 4-4. The different colors within individual layers indicate specific assigned hydraulic conductivities and no-flow zones that are described in subsequent sections.

4.6 Boundary Conditions and Model Stresses

Most of the PRB was encompassed by the model domain; however, no-flow boundaries were input within the outcrop of the Tullock member in the southwestern boundary of the model. Inflow to the model in this area was simulated using constant head cells. Outcrops (no-flow), perennial rivers (constant heads or drains), and ephemeral rivers (drains) were input into the model as boundary conditions based on physical features of the PRB. Stresses on the model included CBM wells (drains), coal mines (drains), municipal supply wells (wells), flowing artesian wells (drains), and spatial infiltration (recharge). These boundary conditions and model stresses are described in more detail in the following sections.



LEGEND

- No Flow Node
- Alluvium
- Shallow Wasatch Sands
- Confining Unit within Wasatch
- Intermediate Wasatch Sands
- Deep Wasatch Sands
- Confining Unit at Wasatch Base
- Ft. Union Coal (Wyodak)
- Ft. Union Coal Units
- Confining Unit Between Ft. Union Coals
- Confining Unit at Base of Coal Units
- Lower Ft. Union
- Lower Ft. Union Sand Aquifer Units

Note: Coordinate System: NAD 27 UTM Zone 13 Meters
colors within cross sections represent different values
hydraulic conductivity

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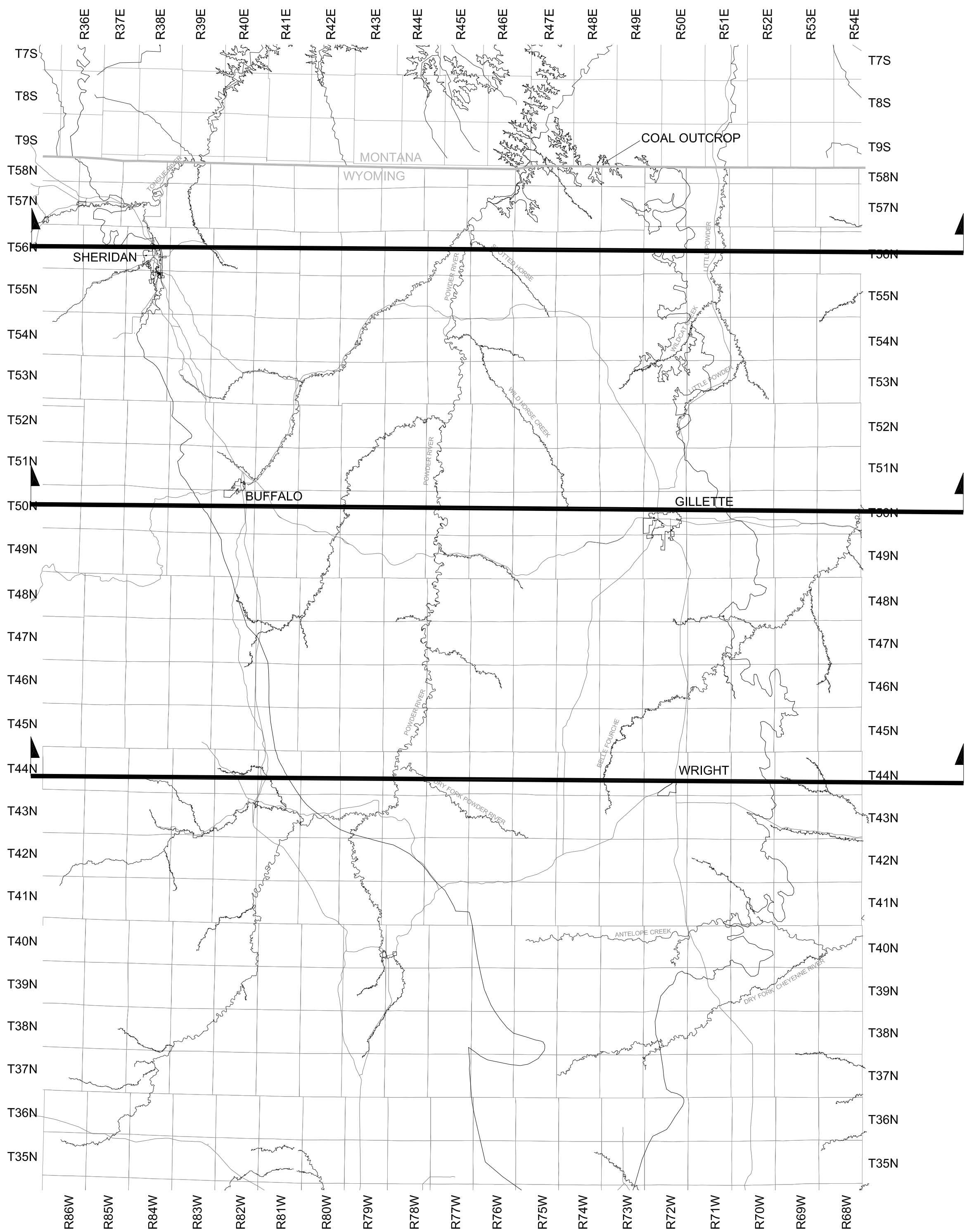
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 4-3
CROSS SECTIONS
OF MODELED LAYERS

MODEL RUN: From 1999-2200 (08-26-02)	
Date: 09/04/02	Drawing File: Figure 4-3.dwg
Scale: As Noted	Drawn By: ETC

Figure 4-3 continued (11x17)



LEGEND

Rivers

Roads

Towns

Cross Section Locations

N

0 11 22 44 Miles

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TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 4-4
CROSS-SECTION
LOCATION MAP

ANALYSIS AREA: CAMPBELL, CONVERSE, JOHNSON & SHERIDAN COUNTIES, WYOMING

Date: 09/04/02	Drawing File: Figure 4-4.dwg
Scale: As Noted	Drawn By: ETC

Different model boundary conditions were used to represent perennial and ephemeral surface flows, mining operations, CBM development, and zones of recharge. Boundary conditions are typically input into the model through the VMODFLOW graphical user interface (GUI). However, given the large number of boundary nodes needed for this model (more than 50,000 CBM wells, more than 15 mining operations, perennial and ephemeral rivers or streams, and different zones of recharge), it was necessary to streamline the process using other programs rather than enter all of the boundary conditions through standard entry routines provided by the VMODFLOW program.

ArcView, MS Access, Excel, PFE, Surfer, AutoCAD, and various FORTRAN programs were used to streamline the boundary input process. First, the model structure (i, j, k data of each node for each layer) was put into a file format that could be shared with other applications. A FORTRAN program was developed to extract this information from the MODFLOW boundary file (.bcf) and write it to a text file. A text file was created for each layer and was then imported into Access. Next, the corresponding X-Y coordinate was determined for each model node i, j using ArcView to define the node boundaries. Another FORTRAN program was developed to transform the model grid into a geo-referenced shape file. Using ArcView, coordinate information was imported and then changed into a shape file. This shape file was joined to the geo-referenced gird. Each boundary location was then assigned a corresponding model node i,j. The database file (.dbf) associated with the shape file (.shp) was then imported into the Access database.

Each model boundary was assigned an elevation using a series of queries in Access linked on layer-row-column. For example, CBM wells were input into the model as drain boundaries. A drain boundary requires a start time (in days), a stop time (in days), the elevation of the drain, and the conductance of the drain. The model accounts for more than 39,000 projected CBM wells and more than 12,000 existing wells. The locations of the projected wells were developed in ArcView. The well location shape file was spatially joined with the model grid shape file, and each well location was assigned a row-column. The .dbf file associated with the well location shape file was then imported into Access.

Using a query that was linked on layer-row-column, each projected well was assigned to a layer depending on where the well was placed within the basin and the number of developed coal seams at the location. For CBM wells, each drain boundary was assigned an elevation 16 feet (5 meters) above the top of the highest developed coal unit in that area. (This elevation was used because most CBM operators in the PRB depressurize wells with submersible pumps set close to the base of the well casing, with shut-off switches set above the pump. This system effectively limits depressurization to a level typically between 10 and 20 feet above the top of the coal.) The results of this query were then exported to Excel. The Excel file was formatted and used as input for another FORTRAN program that was developed to translate data from a spreadsheet format into the VMODFLOW boundary file (.vmb) format. The data were then copied to the existing .vmb file. Following is a summary of the process:

1. Create a shape file using an existing table that contains X-Y coordinates for each location.
2. Perform a spatial join on the new shape file to the model grid shape file.
3. Export the X-Y and i-j coordinates for each boundary location.
4. Import X,Y,i, j into Access.
5. Assign each boundary to a layer.
6. Query (linked on row-column-layer) to obtain the elevation at each point. Manipulate the elevation if necessary.
7. Export the data to an Excel spreadsheet.
8. Format the data.
9. Run the data through a FORTRAN program that translates them into the .vmb file format.

10. Copy the data to the .vmb file.

4.6.1 No-flow Cells

No-flow cells were assigned to areas outside the outcrop of the geologic units represented by the model layer. The extent of no-flow cells varies, depending on the layer represented. Using no-flow cells to represent outcrops helps mitigate the effects of displacement caused by minimum layer thickness. The no-flow cell configurations for some layers were identical, but in general, the deeper the layer, the fewer no-flow cells surrounded the active area. Recharge was applied to the highest active cell. In effect, the highest active cell acts as if it were at ground surface. The extent of no-flow cells for layer 14 (Lowermost Fort Union Coal Group) is shown in Figure 4-1.

No-flow cells were also designated in river areas where the river elevation was below the base of any layer. Some of the “fingers” along the coal outcrop were also set as no-flow cells because they contribute very little to the regional flow system, but can cause numerical convergence issues.

4.6.2 Recharge

The locations of recharge areas in the model are shown in Figure 4-5. With the exception of the largest rivers, most of the streams are intermittent or ephemeral. Recharge to groundwater aquifers occurs from infiltration of direct precipitation (rain and snowmelt), runoff in stream valleys, and standing water in playas, reservoirs, and stock ponds.

Recharge into the subsurface from precipitation is a small percentage of the total precipitation over most of the area because the climate and surface features restrict significant infiltration. The majority of precipitation runs off or evapotranspires. Given the large areal extent of the PRB, however, that small percentage of the available precipitation that infiltrates the surface does provide significant recharge to the subsurface. Average area-wide recharge, which includes recharge in stream valleys and ponds, expressed over the entire area is expected to be less than 1 percent of the total precipitation or equivalent to less than 0.1 to 0.15 inches per year. Steady-state calibration, described in Section 5, indicated that this amount of area-wide recharge appears realistic. A value of 0.03 inches per year was indicated by the steady-state calibration.

Infiltration rates are greater in areas that contain surface geologic units that are more permeable, such as the clinker that occurs along the eastern and northern outcrop areas of the upper Fort Union coal zone, and in the eastern portion of the PRB along the outcrop of Wasatch coals. The clinker areas are generally considered to form significant recharge areas for the coal However, as noted in Section 2.2, the rate of recharge to the coal may be limited by the presence of a low-permeability zone at the contact between the clinker and underlying coal or shale. Thick, clay-rich soils over flatter surfaces also may retard the downward movement of water (Heffern and Coates 1999.) Pre-mining potentiometric data and interpretations from many of the permit applications for the coal mines tend to support this assumption. The clinker provides a continuous source of recharge to the coal through ponding of water, albeit at a relatively slow rate because of the low-permeability transition zone. Recharge in the clinker areas is expected to be in the range of 5 to 10 percent of total precipitation or equivalent to between 0.5 to 1.5 inches per year. Steady-state calibration, described in Section 5, indicated that this range of recharge in the clinker areas appears realistic. Values of 0.1 inch per year for clinker associated with coals of the Wasatch Formation and 0.6 inch per year for clinker associated with the Fort Union coal zone were indicated by the steady-state calibration.

Infiltration of surface water in creek valleys and in impoundments is generally considered an important source of recharge to shallow aquifers, as discussed in Section 2.3. Additional water is available to infiltrate into the underlying alluvium and bedrock formations within valleys where discharge of CBM produced water into surface drainages has resulted in perennial flow conditions. Similarly, water stored in impoundments can leak into the underlying shallow groundwater.

The actual amount of recharge in any watershed depends on the distribution of water handling methods employed for managing CBM produced, water as described in Chapter 3. The effects of the various water handling methods were simulated in the model by applying additional recharge to each sub-watershed on a year-by-year basis during the production period. The amount of additional recharge was based on a combination of the amount of water produced, the projected percentage of water handled by the various methods, and the projected infiltration of the water handling method. The net recharge for each sub-watershed (shown as a percent of CBM water production for that sub-watershed) is summarized for each of the water handling scenarios in Tables 4-3 through 4-5.

The additional recharge was converted to a year-by-year infiltration rate based on the area of CBM development in each sub-watershed. For the model, the area of CBM development was considered to be the extent of CBM development plus a one-half mile buffer. The areas of enhanced recharge are shown in Figure 4-5.

4.6.3 Rivers

Rivers in the PRB may act as either recharge or discharge areas for shallow groundwater, depending on the elevation of water in the river compared with the head elevation in the adjacent shallow aquifer. The Powder River is interpreted to be a discharge area for groundwater in the PRB, particularly in the northern part of the basin, because upward vertical flow gradients generally prevail in the vicinity of the river. However, as explained in previous sections of this report, baseflow in the Powder River is not discernible because the small amount that occurs is lost through evapotranspiration. The Belle Fourche, Little Powder, and Cheyenne Rivers and their major tributaries are also considered to interact with shallow groundwater, although they may act as recharge areas along certain reaches, and discharge areas along other reaches.

The model simulates interactions between rivers and adjacent shallow aquifers using “constant head” nodes to represent major perennial streams and “drain” nodes to represent major ephemeral streams. Constant head nodes were input along the courses of the Powder River, Belle Fourche River, Crazy Woman Creek, Clear Creek and Tongue River and their major tributaries. The elevation set in the constant head nodes and the drain nodes was based on the topographic elevation of the river at each node location, trending in a linear manner downstream. The locations of the river constant head and drain nodes are shown on Figure 4-6. This figure consolidates the boundary conditions representing river cells from all of the model layers.

4.6.4 Drains (Mines)

The model simulates active surface coal mining by setting “drain” nodes in the target coal group layer at the appropriate locations. Groundwater will enter an active drain node from an adjacent node as long as the potentiometric level in the adjacent node is higher than the drain elevation. As the potentiometric elevation in the adjacent node is lowered by drainage, the rate of drainage decreases. Drain nodes can be made inactive by setting the drain elevation much higher than the adjacent node potentiometric elevation. Unlike constant head or general head nodes, drain nodes cannot add water to adjacent nodes. The use of drain nodes to simulate surface mining allows the water levels to recover when active mined areas are backfilled and reclaimed.

Table 4-3
Summary of the Net Recharge for Each Sub-Watershed – Alternatives 1 and 3

	Water Handling Method					Recharge to Groundwater (Fort Union coal zone and above)								
	Surface Discharge (percent)	Infiltration Impoundment (percent)	Containment Impoundment (percent)	Land Application (percent)	Injection (percent)	Surface Discharge (percent)	Infiltration Impoundment (percent)	Containment Impoundment (percent)	Injection (percent)	TOTAL (percent)	Runoff (percent)	Surface Discharge Evapotranspiration (percent)	Impoundment Storage and Evaporation (percent)	Consumptive Use (percent)
Upper Tongue River	35	45	10	0	10	7	26	0	0	33	34	2	23	0
Upper Powder River	75	15	5	0	5	13	9	0	0	22	62	3	9	0
Salt Creek	55	35	5	0	5	10	20	0	0	30	48	2	15	0
Crazy Woman Creek	70	5	5	15	5	12	3	0	0	15	57	3	6	15
Clear Creek	35	40	5	10	10	7	23	0	0	30	33	1	16	10
Middle Powder River	65	10	10	10	5	11	6	0	0	17	54	2	13	10
Little Powder River	65	10	10	10	5	11	6	0	0	17	54	2	13	10
Antelope Creek	55	35	5	0	5	10	20	0	0	30	48	2	15	0
Upper Cheyenne River	55	35	5	0	5	10	20	0	0	30	48	2	15	0
Upper Belle Fourche River	45	40	5	0	10	8	23	0	0	31	41	2	16	0

Note:
Injection zones would occur below the Fort Union coal zone and would not contribute to recharge of the coal zone aquifer

Totals may differ from 100 percent as a result of independent rounding

Table 4-4
Summary of the Net Recharge for Each Sub-Watershed – Alternative 2A

	Water Handling Method					Recharge to Groundwater (Fort Union coal zone and above)								
	Surface Discharge (percent)	Infiltration Impoundment (percent)	Containment Impoundment (percent)	Land Application (percent)	Injection (percent)	Surface Discharge (percent)	Infiltration Impoundment (percent)	Containment Impoundment (percent)	Injection (percent)	TOTAL (percent)	Runoff (percent)	Surface Discharge Evapotranspiration (percent)	Impoundment Storage and Evaporation (percent)	Consumptive Use (percent)
Upper Tongue River	5	65	5	15	10	2	37	0	0	39	12	1	23	15
Upper Powder River	30	60	0	5	5	6	34	0	0	40	31	1	17	5
Salt Creek	0	70	5	5	20	2	40	0	0	42	9	0	25	5
Crazy Woman Creek	5	70	5	10	10	3	40	0	0	43	13	1	25	10
Clear Creek	5	70	5	10	10	3	40	0	0	43	13	1	25	10
Middle Powder River	30	55	0	10	5	6	31	0	0	37	30	1	15	10
Little Powder River	40	45	0	10	5	8	26	0	0	34	38	2	13	10
Antelope Creek	60	30	0	5	5	11	17	0	0	28	52	2	8	5
Upper Cheyenne River	60	30	0	5	5	11	17	0	0	28	52	2	8	5
Upper Belle Fourche River	60	30	0	5	5	11	17	0	0	28	52	2	8	5

Note:
Injection zones would occur below the Fort Union coal zone and would not contribute to recharge of the coal zone aquifer

Totals may differ from 100 percent as a result of independent rounding

Table 4-5
Summary of the Net Recharge for Each Sub-Watershed – Alternative 2B

	Water Handling Method					Recharge to Groundwater (Fort Union coal zone and above)								
	Surface Discharge (percent)	Infiltration Impoundment (percent)	Containment Impoundment (percent)	Land Application (percent)	Injection (percent)	Surface Discharge (percent)	Infiltration Impoundment (percent)	Containment Impoundment (percent)	Injection (percent)	TOTAL (percent)	Runoff (percent)	Surface Discharge Evapotranspiration (percent)	Impoundment Storage and Evaporation (percent)	Consumptive Use (percent)
Upper Tongue River	5	45	5	15	10	2	26	0	0	28	10	0	18	35
Upper Powder River	30	40	5	5	5	6	23	0	0	29	29	1	16	20
Salt Creek	0	50	10	5	20	1	28	0	0	29	6	0	24	20
Crazy Woman Creek	5	45	5	15	10	2	26	0	0	28	10	0	18	35
Clear Creek	5	50	5	10	10	2	28	0	0	30	10	0	19	30
Middle Powder River	30	40	5	10	5	6	23	0	0	29	29	1	16	20
Little Powder River	40	25	0	10	5	7	14	0	0	21	35	2	7	30
Antelope Creek	60	25	0	5	0	10	14	0	0	24	51	2	7	15
Upper Cheyenne River	60	25	0	5	0	10	14	0	0	24	51	2	7	15
Upper Belle Fourche River	60	30	0	5	5	11	17	0	0	28	52	2	8	5

Notes:

Injection zones would occur below the Fort Union coal zone and would not contribute to recharge of the coal zone aquifer

One hundred percent of the water handled by active treatment under Alternative 2B (reference FEIS Table 2-22) would be used consumptively

Totals may differ from 100 percent as a result of independent rounding

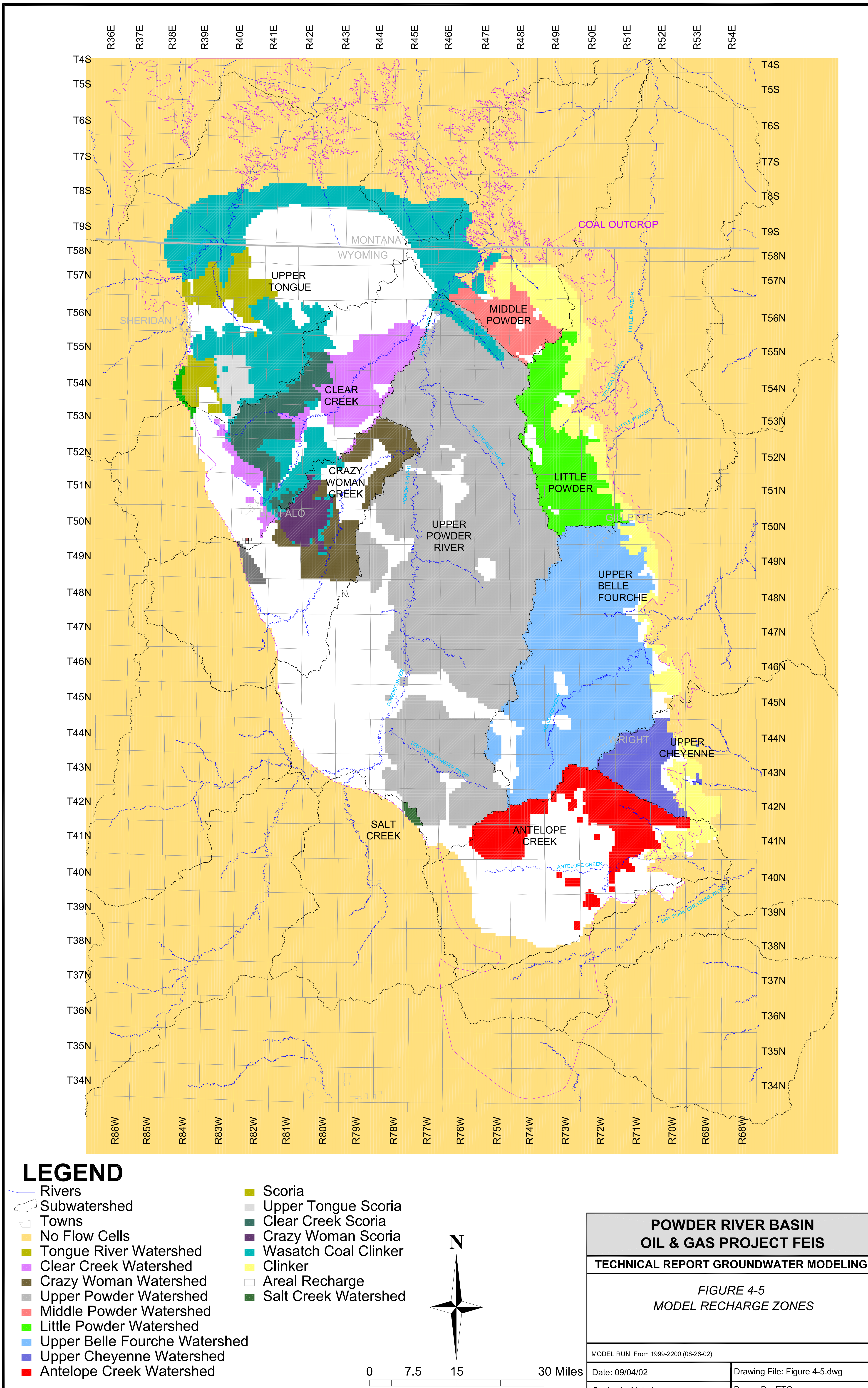


FIGURE 4-5
MODEL RECHARGE ZONES

Figure 4-5 continued (11x17)

Where mining occurs, the mining sequence was simulated from reasonably foreseeable mine plans as incremental impacts in 1-year stress periods from approximately 1975 (the earliest mining along the PRB outcrop areas, with the exception of the Wyodak mine east of Gillette) to 2033. Each drain node is turned on during the period of active mining in the area represented by the node, a 3-year period.. After this period, the drain node becomes inactive, which simulates backfilling and reclaiming of the pit area after active mining. The location and timing of drain nodes were based on historical mining records and life of mine plan maps included in mining permit applications and 5-year mining plan updates. It is understood that life-of-mine plans are dynamic and may change in future years, but they provide a general projection of likely coal removal sequences and mine progression. The mining permit areas and the extent of drain nodes representing these mine areas are shown in Figure 4-7. The drain node water level in an active mine area is set a few feet above the bottom elevation of the coal layer. Since the elevation of the coal bottom varies geographically, each drain node is input individually with a different elevation.

4.6.5 Drains (CBM Wells)

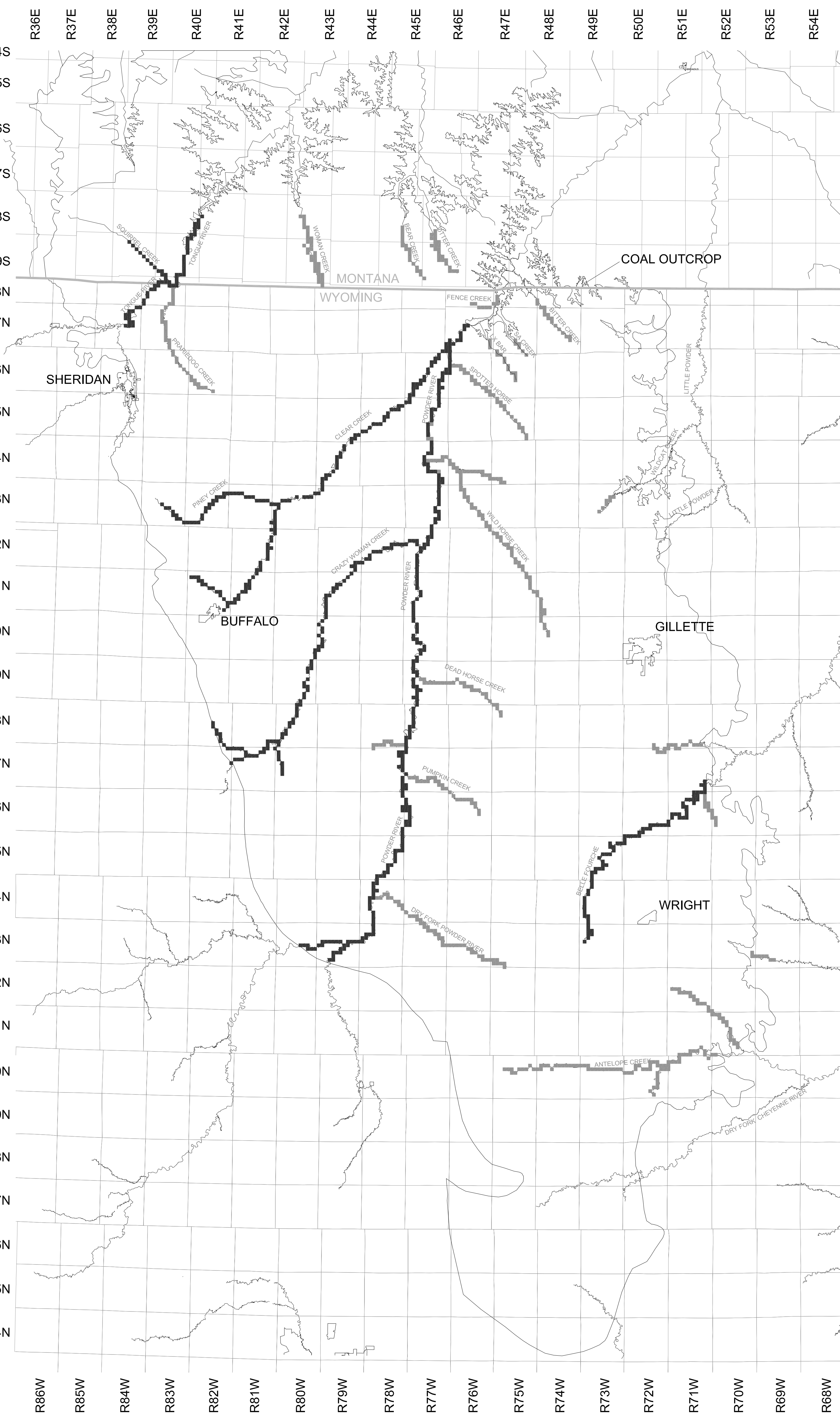
Active CBM wells are simulated in the model by setting "drain" nodes in the target coal group layer. Groundwater will enter an active drain node from an adjacent node as long as the potentiometric level in the adjacent node is higher than the drain elevation. Water flow to the drain declines as the potentiometric head declines in the model nodes surrounding the drain. This decline simulates the process that occurs during CBM production, where declines in water production over time typically are observed.

Depressurization of the coal zone aquifer was simulated as incremental impacts in 1-year stress periods from approximately 1989 (the earliest CBM production) to the presently anticipated end-of-CBM operations in 2018 for locations developed or projected to be developed. The location and timing of drain nodes representing existing CBM wells were based on data from WOGCC. Future CBM development is based on the Proposed Action development scenario described in Chapter 3.

Each drain node is activated during the period of active CBM operations in the area represented by the node. The water level in the drain node for an active CBM well is set about 16 feet above the top elevation of the highest coal unit being developed at that location. For example, if four coal units are being developed at a single location, drain nodes are placed in each of the coal layers, but the elevation of each drain is set at 16 feet above the highest active coal. The majority of drain boundaries representing CBM wells were placed in the lower coal layers of the model. After all CBM production ceases in the node, the drain node is made inactive by setting the drain elevation above ground surface, which allows the water level in the node to recover.

The model used water production data from WOGCC as the source for input of drains during the period from 1988 to March 2001. A total of 6,098 wells show some water production during this time. The productive life of wells that were still operating in March 2001was assumed to be 7 years from the start of production. A total of 3,677 permitted wells were assumed to begin production during March 2001 to March 2002. These wells were assigned a 7-year life span. It is assumed that future wells would be drilled over a 10-year period from March 2002 through March 2012. Each future well would have a 7-year life span, as described Chapter 2 of the FEIS. A total of 39,367 future wells were input into the model as drain nodes, with appropriate time schedules.

CBM wells in Montana were not included in the regional model for the following reasons. First, the regional model used to project impacts from CBM development in Wyoming requires some input parameters that could not be estimated for the proposed CBM wells in Montana. Detailed information on water handling methods that was not available would have been needed to account for infiltration and recharge in the model for the projected CBM wells in Montana.. In addition, the regional model was designed to provide a conservative estimate of the upper limits of water production in Wyoming. If CBM wells in Montana had been included in the regional model, the effect would have been to decrease water production from some nearby CBM wells in Wyoming. The exclusion of CBM wells in Montana from the regional model likely resulted in underestimation of the extent of impacts to the potentiometric surface in some areas near the state line between Wyoming and Montana while overestimating the amount of production from some CBM wells in Wyoming.



LEGEND

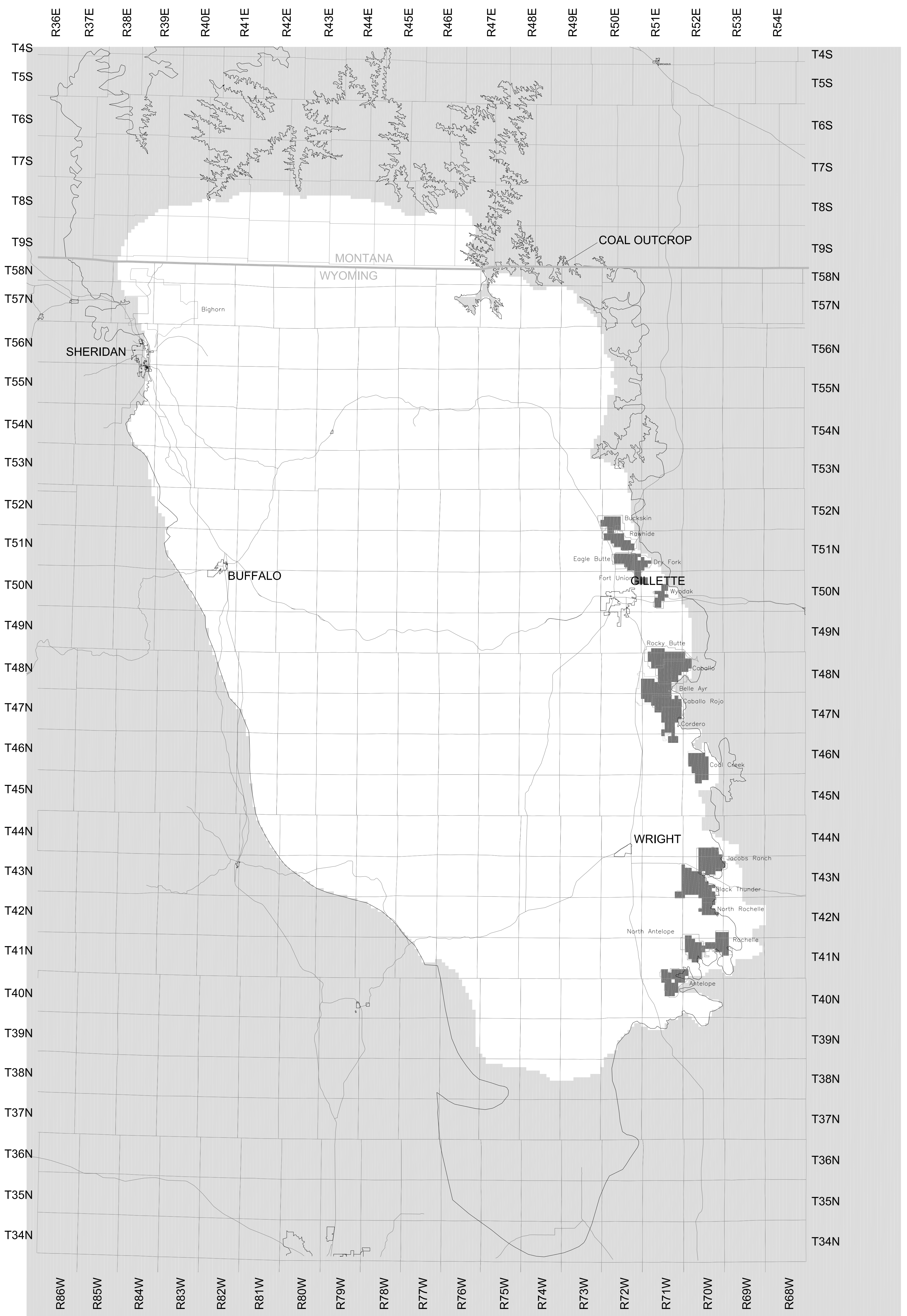
- Rivers
- ■ Constant Head Node Representing a Perennial Stream or River
- ■ Drain Node Representating an Ephemeral Stream
- Towns

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS	
TECHNICAL REPORT GROUNDWATER MODELING	
FIGURE 4-6 MODEL DRAIN NODES REPRESENTING STREAMS OR RIVERS	
MODEL RUN: From 1999-2200 (08-26-02)	
Date: 09/04/02	Drawing File: Figure 4-6.dwg
Scale: As Noted	Drawn By: ETC

Figure 4-6 continued (11x17)



LEGEND

- Towns
- Roads
- No Flow Cells
- Drain Node Representing Mining

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS	
TECHNICAL REPORT GROUNDWATER MODELING	
FIGURE 4-7 *MODEL DRAIN* *(MINE) NODES*	
MODEL RUN: From 1999-2200 (08-26-02)	
Date: 09/04/02	Drawing File: Figure 4-7.dwg
Scale: As Noted	Drawn By: ETC

Figure 4-7 continued (11x17)

The producing intervals of the wells were distributed among the four coal-bearing units (which are represented by layers in the model) based on existing production or the thickness and depths of the coals in any area. In many areas, more than one coal interval would be produced and this is reflected in the model where more than one well per well pad is projected. Input of the CBM wells as drain boundaries in the model was aided using ArcView, Access, and Fortran programs, as described earlier in this section. It is possible for several wells to produce from the same model grid node at the same time. Multiple CBM wells at the same grid node were represented by a single drain boundary. The number of operating wells simulated by the drain boundary was adjusted as production started and stopped. This was accomplished by adjusting the drain conductance proportionally to the number of wells operating during each year. Drain conductance was established from steady state and transient state calibration to production data at several wells in each watershed where data were available. Figure 4-8 shows the composite (all four coal layers) locations of CBM drain nodes that were input into the model.

4.6.6 Pumping from Municipal Water Supply Wells

The communities of Gillette and Wright, as well as many subdivisions that surround Gillette, obtain much of their municipal water supply from wells screened within the sands of the lower Tongue River, Lebo, and Tullock members of the Fort Union Formation (HKM 1994). Generally, these water supply wells are completed in aquifer units that underlie the upper Fort Union coal zone. Pumping wells were included in the model to represent municipal water supply wells for the City of Gillette, the community of Wright and several subdivisions around Gillette, including Antelope Valley, Crestview, and Sleepy Hollow. These wells were included in layer 17, representing the Fort Union Formation below the upper Fort Union coal zone. Well locations and average pumping rates were obtained from well completion reports (HKM 1993; Wester-Wetstein, 1994, 1999c, 1999e).

4.6.7 Flowing Artesian Wells

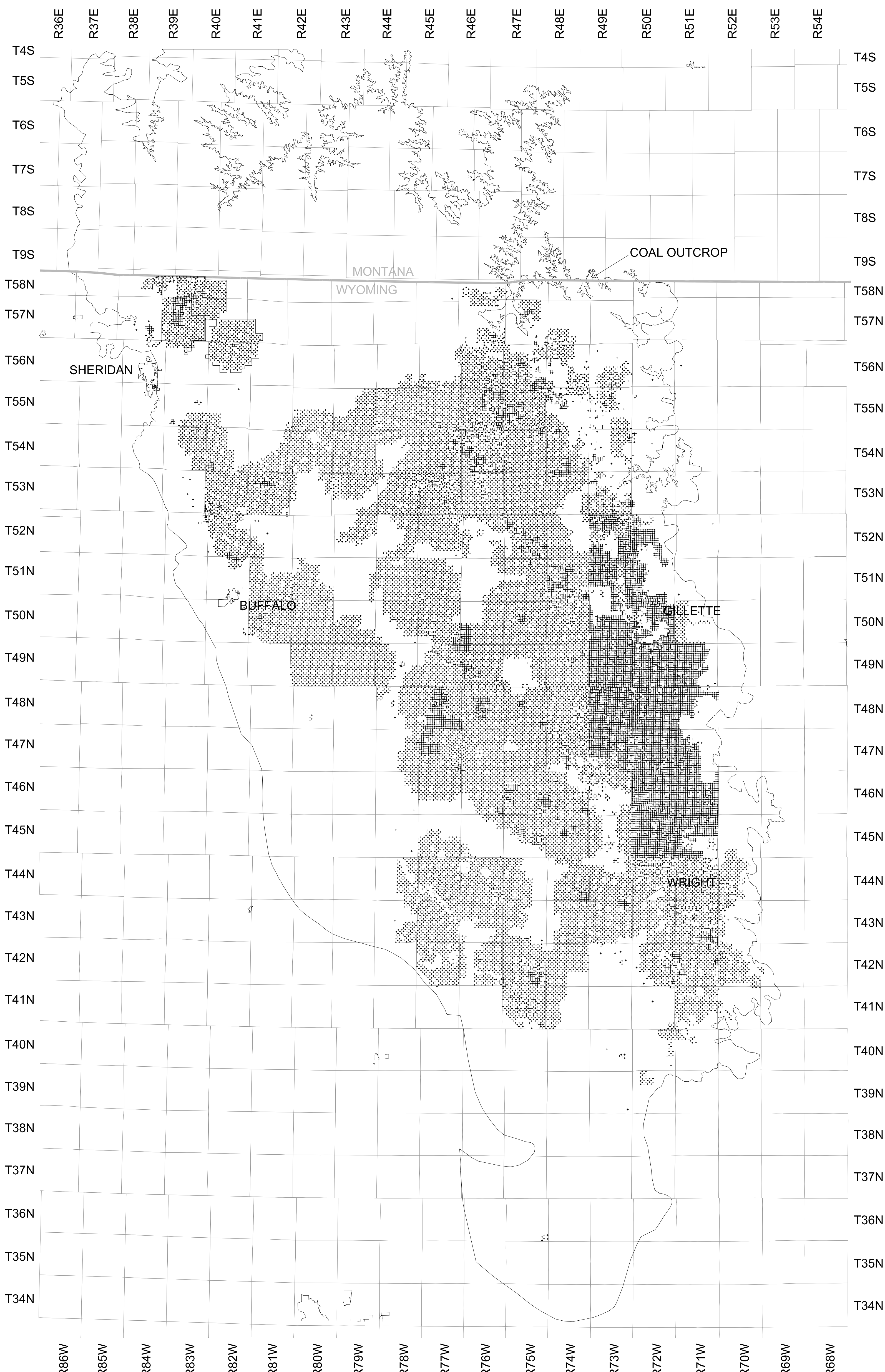
Numerous flowing artesian wells are present in the northern portion of the model area. These wells were operating before the start of the model simulation period (1975) and have continued to operate. The effect of these wells was incorporated into the model using low-conductivity drain cells located in the uppermost coal unit in areas where these wells are known to be present.

4.7 Aquifer Properties

A summary of the range of model input parameters assigned to the various geologic units in the model is given in Table 4-6.

4.7.1 Hydraulic Conductivity

The hydraulic conductivity of a material is a measure of the ease that water can pass through the material under a specified hydraulic gradient.A range of values for hydraulic conductivity was used for each layer for the regional PRB model. Values for hydraulic conductivity of the various geologic units were based on actual field data (results of pumping tests) and model calibration to both steady-state and transient-state conditions. The ranges of values used for various lithologies in the model layers are summarized in Table 4-6.Several lithologies or conditions may be represented within one layer. For example, values of hydraulic conductivity vary in the layers that represent the coal groups of the upper Fort Union Formation (layers 8, 10, 12 and 14), representing clinker at the outcrop and fracture zones within the coal.



LEGEND

+ CBM Nodes

Towns

N

0 7.5 15 30 Miles

POWDER RIVER BASIN
OIL & GAS PROJECT FEIS

TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 4-8
MODEL DRAIN
(CBM) NODES

MODEL RUN: From 1999-2200 (08-26-02)

Date: 09/04/02	Drawing File: Figure 4-8.dwg
Scale: As Noted	Drawn By: ETC

Figure 4-8 continued (11x17)

Table 4-6
Summary of Regional Model Input Parameters

Formation	Model Layer	$K_{x,y}$ (ft/s)	K_z (ft/s)	S_s (1/m)	S_Y (unitless)	Porosity (%)
Alluvium	1 - 7	1e-5	3e-6	1e-4	.2	25
Ancient Alluvium	1-4	1e-5	3e-6	5e-6	5e-4	10
Wasatch – Confining	1	1e-8	3e-9	5e-6	5e-4	10
Generalized Wasatch	2	1e-7	3e-8	1e-4	.02	10
Wasatch – Sand	4	2e-6	2e-7	1e-4	.02	10
Wasatch – Confining	3,5	2e-8	2e-10	5e-6	5e-4	10
Wasatch – Sand	6	2e-6	2e-7	1e-4	.02	10
Wasatch – Lower Confining	7	1e-8	6e-11	5e-6	5e-4	10
Upper Fort Union Coal Unit 1	8	1e-4 to 6e-5	1e-5	1e-6	1e-3	1
Upper Fort Union Confining	9	6e-8	6e-10	5e-6	5e-4	10
Upper Fort Union Coal Unit 2	10	6e-5	1e-5	1e-6	1e-3	1
Upper Fort Union Confining	11	6e-8	6e-10	5e-6	5e-4	10
Upper Fort Union Coal Unit 3	12	6e-5	1e-5	1e-6	1e-3	1
Upper Fort Union Confining	13	3e-9	6e-10	5e-6	5e-4	10
Upper Fort Union Coal Unit 4	14	1e-4 to 8e-5	8e-6	1e-6 to 2e-6	1e-3	1
Fort Union – Lower Confining	15	1e-8	5e-10	5e-6	5e-4	10
Middle Fort Union Lebo Shale	16	1e-8	1e-9	1e-4	0.02	10
Lower Fort Union Tullock	17	1e-7	3e-8	5e-4	0.01	25
Clinker	1 - 13	2e-5 to 6e-5	6e-5 to 2 e-6	0.01	0.1	25
Generalized Fort Union	8, 10, 12, 14	1e-6 to 3e-7	9e-8 to 2e-9	9e-5 to 5e-6	.0005 to 0.0125	10-25

$K_{x,y}$ = hydraulic conductivity (horizontal)
K_z = hydraulic conductivity (vertical)
S_s = specific storage
S_y = specific yield

The coal aquifers, particularly in the eastern PRB, have been subject to numerous field pumping tests. These tests have been evaluated in some detail in earlier studies (BLM 1994). A summary of hydrologic parameters derived from multi-well tests conducted in the PRB is included in Appendix B. Multiple well pumping tests, which rely on interpretation of observation wells that surround the pumping well, yield much more reliable and representative estimates of the hydraulic conductivity in an area. The values for hydraulic conductivity obtained from single-well pumping tests are less reliable because they tend to reflect the local conditions around the wellbore and so were not included in the summary of testing in Appendix B. The values for hydraulic conductivity derived from more reliable multi-well coal pumping tests fall within the range of 4.6×10^{-7} to 8.6×10^{-4} feet per second (ft/sec), with a median value of 2.3×10^{-5} ft/sec (Appendix B). Water yields from coal wells vary widely, from less than l gpm to more than 100 gpm. The wide range reflects the extent of fracturing and cleating in the vicinity of the well bore. Development and hydraulic fracturing of coal wells can significantly increase individual well yields.

The ranges of hydraulic conductivities derived from multi-well pumping tests were used as starting points for estimates of hydraulic conductivity in the regional model for any area. Even data from long-term multi-well coal pumping tests may not be representative of regional transmissivities, which tend to be dominated by major fracture zones in the coal. Accordingly, the range in values for hydraulic conductivity used in the model was based primarily on matching to steady-state and transient-state conditions.

The flatter, pre-mining potentiometric gradient in the southeastern part of the PRB (see Section 2.3) might suggest higher hydraulic conductivity for the coal in this area. Bloyd et al. (1986) suggest that this relatively flat potentiometric surface is questionable because it is based on very few data points, some of which are of suspect accuracy.

Hydraulic conductivity may be anisotropic, meaning that it changes depending on the direction of water movement. The MODFLOW model allows hydraulic conductivity to be input for each node in the three principal directions, corresponding to the three perpendicular axes of the model grid.The hydraulic conductivity in the horizontal direction (the x- and y- directions) was assumed to be uniform for the regional model. Although there is evidence to suggest that the coal exhibits some anisotropy caused by cleating and fracturing, studies show that the direction of anisotropy varies significantly over the PRB. In a regional sense, the simplification to isotropic conditions is believed to be a reasonable accommodation. The effect of fracturing on regional permeability was taken into account by assigning much higher hydraulic conductivities along the length of the major fracture traces or lineaments identified in the model area.

There is considerably less information on the hydraulic conductivity of the Wasatch sand aquifers. The nature of the Wasatch Formation, with discontinuous interbedded sands, silts, and clays, also results in considerable variability. Values derived from testing, summarized in Appendix B, range from 2.3×10^{-7} to 2.3×10^{-4} ft/sec, with a median value of 6.2×10^{-5} ft/sec. Accordingly, the range of values for hydraulic conductivity used in the model was based primarily on matching to steady-state and transient-state conditions. In general, the sandier Wasatch units will tend to dominate the overall horizontal conductivity, while the silt and clay units dominate the overall vertical conductivity. The assigned horizontal conductivity for most of the Wasatch Formation was representative of a fine- to medium-grained sand (2×10^{-6} ft/sec). The vertical conductivity was representative of silty clay (3×10^{-8} ft/sec). A small area close to the Powder River where the Wasatch Formation contains more sand was assigned a horizontal conductivity of 1×10^{-5} ft/sec.

The vertical hydraulic conductivity is typically one to two orders of magnitude lower than the horizontal value. The vertical hydraulic conductivity is an important parameter that controls the extent of influence in aquifer units above and below the pumped target coal seam. There are very little data from direct testing of this parameter. Vertical hydraulic conductivity of confining units was tested directly for the Ruby Ranch Project Permit Application (Power Resources, Inc. 1999) and is summarized in Appendix B. Measured values for claystone ranged from 2.8×10^{-10} ft/sec to 1.1×10^{-9} ft/sec. The range of vertical hydraulic conductivity values used in the model was based primarily on matching to steady-state and transient-state conditions. Modeling in the Caballo Creek area (Chapter 8) indicated that the vertical hydraulic conductivity of the claystone confining units above and below the coal zone (layers 7 and 15) ranges between 6×10^{-11} ft/sec and 5×10^{-10} ft/sec.

4.7.2 Storage Coefficient and Specific Storage

The range of values for storativity used for the various model layers are summarized in Table 4-7. There are relatively few reliable data on storage coefficients in the PRB. A compilation of values derived from multi-well pumping tests in the PRB is included in Appendix B. Storage coefficient values vary significantly, depending on whether the unit tested is under confined or unconfined conditions. Most pumping tests conducted in the coal are considered under confined conditions. Storage coefficients derived from these pumping tests are in the range of 10^{-3} to 10^{-5}. The specific storage (S_s, equivalent to the storage coefficient divided by the thickness) for these tests ranged between 2.1×10^{-7} ft^{-1} and

$1.9x10^{-4}$ ft^{-1}, with a median value of $3.8x10^{-6}$ ft^{-1} Pumping tests conducted in the Wasatch sands may be under confined or unconfined conditions. Storage coefficients derived from these pumping tests are in the range of 10^{-2} to 10^{-6}. The specific storage derived from Wasatch sand tests averages $1.8x10^{-4}$ ft^{-1}.

4.8 Limitations of Model

4.8.1 Size of the Model

As indicated in Section 4.1, any regional model of this size will involve limitations caused by the size of the grid nodes and the simplification of a complex hydrogeologic system necessary for creating the model. The regional model was constructed using averaged and smoothed values so that localized conditions are typically not well refined. The size of each node in the model is one-half mile by one-half mile, so infiltration impoundments, small streams and rivers, and other smaller features cannot be represented exactly. Rather, smaller features are represented by the application of boundary conditions over the entire grid node. For example, infiltration of water from an impoundment is applied over an entire cell as a very small recharge rate. This assumption is less accurate for individual features, but this assumption improves as the density of features within a grid node increases. The primary purpose of modeling a hydrologic system on a regional, basin-wide scale is to project impacts and compare alternatives. A regional model also can be used to estimate the mass water balance so that long-term gain or loss can be evaluated. The regional model is an adequate tool for a comprehensive determination of the effects of CBM development. However, the results should be viewed in perspective with the scale, and a sub-regional or local area model should be used to help evaluate impacts on a smaller scale.

Two sub-area models, which are developed at a much smaller scale, complement the regional model and were used to demonstrate specific aspects of CBM development in the PRB. The Caballo Creek sub-area model, described in Chapter 8, was used to match transient water data in an area with a relatively long history of CBM development. This match allowed an evaluation of hydrologic parameters for confining zones that have a major influence on projections of shallow aquifer drawdown and coal recovery after CBM pumping ends. The LX-Bar sub-area model, described in Chapter 9, was developed specifically to examine the potential influences of impoundment infiltration and adjacent creek flows on groundwater levels in shallow Wasatch sands in an area where surface discharge would probably be limited by water quality considerations.

4.8.2 Lack of Geologic Data for the Wasatch Formation

The Fort Union coal units are reasonably well defined in the regional model, but the Wasatch units lack adequate definition. The Wasatch Formation is highly variable throughout the basin but, lacking sufficient geologic data, the Wasatch Formation was arbitrarily divided into six layers in the model. The primary reason for dividing the Wasatch Formation is to provide adequate vertical discretization, although not exact geologic definition, in the model. Greater vertical discretization improves the way MODFLOW handles the vertical movement of water. Hydraulic conductivities for each layer are set so that the overall conductivity of the Wasatch Formation is simulated.

4.8.3 Representation of CBM Wells as Drain Boundary Nodes

In the regional model, CBM wells were simulated using drain boundary nodes. Any node could encompass one to four actual CBM wells per layer and up to 16 wells per model column. The number of CBM wells represented per drain was accommodated by varying the drain conductance. Use of a drain boundary applied over the entire node to represent a CBM well, which is a single point within the node, will over-predict the water production of a single well during the early stages of production. As well density increases within a given node, however, the drain boundary becomes a better representation of CBM production.

4.8.4 Lack of Data in the Central and Western Parts of the Basin

There are a lack of data for observation wells, production, and geology for the Wasatch Formation away from established areas of development in the eastern portion of the basin. The model is limited and potentially skewed by the data that are available. Model results from areas of the basin that lack adequate calibration data should be considered only as a general indicator of potential impacts. The model should be updated and refined as new data become available.

4.8.5 Dry Cells

In MODFLOW, a cell is changed from an active cell to a dry cell when the head in that cell falls below the base of the cell. When a cell becomes dry, the model treats it as an inactive cell, and water cannot move through it. Also, if a cell becomes dry, any boundary conditions will effectively be removed from the model. For example, if a cell becomes dry in layer one, any recharge applied to that cell is lost unless it is specified that recharge be applied to the highest active cell within a column, as was the case in the PRB EIS model. If the entire column of cells becomes dry, however, the recharge will be lost to the system. Dry cells can severely affect the horizontal and vertical movement of water throughout the simulated aquifer system.

Cells can become dry for various reasons, such as simulated mining activity, CBM activity downdip, or steeply dipping beds. It is feasible for dry cells to occur as aquifers are dewatered, but dewatered areas would eventually repressurize and resaturate once development has stopped and water levels are allowed to recover. In the regional model, cells became dry because of mining and CBM development. The MODFLOW rewetting package was used to mitigate the impacts of the dry cells on the results. Rewetting parameters were set such that cells were allowed to rewet from adjacent cells and from cells directly below. The rewetting threshold was set at 5 meters, implying that if the head in an adjacent cell exceeded 5 meters, rewetting would occur, thus changing the dry cell to an active cell. The threshold was set at 0.1 meter, so the head in a dry cell that was activated would be set 0.1 meter above the base of the cell.

Rewetting has its own limitations, particularly with regard to solution convergence. If a cell is continually drying out and rewetting, the model will have difficulty converging. At times during the model run, it may be necessary to increase the solver convergence criteria to enable the model to converge.The convergence criteria were raised as high as 3 meters during some stress periods for the transient regional model. However, the water balance discrepancy for all stress periods was less than 1 percent, and typically was around 0.1 percent, indicating that the model did not converge until a reasonable solution was reached.